Estimation of the Quantity of Water in the Abandoned Underground Mine of Gold Fields Ghana Limited Tarkwa: A Potential Source to Augment Water Supply to Tarkwa Municipality*

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Abstract

The Tarkwa district is an important gold mining area in the Southwestern part of Ghana. The main source of potable water supply to the Tarkwa Nsuaem Municipality is from the Bonsa River treatment plant managed by the Ghana Water Company Limited (GWCL). The River is under threat from serious contamination by illegal mining ("galamsey") activities within its catchment area. Consequently, the amount of water supplied to the Municipality has not kept pace with its growing population due to increasing treatment cost and supply difficulties. The need to find alternative and sustainable sources of potable water supply to augment that from GWCL to the Municipality has become imperative. A large void volume created as a result of the abandoned underground mine operated by Gold Fields Ghana Limited (GFGL), after its closure in 1999 has flooded. This potential water resource is being pumped out daily, and wasted, sometimes spilling-over to low lying areas around the mine when allowed to reach its decant level. This study estimated the quantity of water in the Abontiakoon Vertical Shaft (AVS) which is part of the large underground void using survey production figures and post-closure void filling parameters resulting in 2.8 x 10^6 m^3 and 2.9 x 10^6 m^3 respectively. The rate of recharge to the underground water was also estimated to ascertain the sustainability of the void water should it be considered for use by employing the model of predicting rebound on "void filling" basis and average dewatering rate before closure at 2 535 m^3/day and 2 618 m^3/day respectively; indicating that recharge to the AVS reservoir is about 6 x 10^6 gal/day or 30% of current daily water supply deficit in the TNM. The estimated potential volume of mine water in storage in the entire Tarkwa underground void is 32 x10^6 m^3. Two samples of the mine water were taken in November 2011 and February 2015 for quality analysis, in order to have a fair knowledge of the water quality parameters. The quality of the underground water was found to be potentially good, and not likely to cause any health threats, or water quality problems. Depth sampling is recommended to determine the chemical profile of the reservoir.

Keywords: Reservoir, Municipality, Bonsa River, Contamination, Tarkwa

1 Introduction

Mechanised underground mining in Tarkwa dates back from the 19^{th} century and over the decades, the mine was acquired by different interests with the last one being Gold Fields Ghana Limited (GFGL), Tarkwa Mine in 1993. Access to the ore was through four shafts namely; the Apinto Shaft, Fanti South Shaft, Ferguson Shaft and the Abontiakoon Vertical Shaft (AVS). The AVS served as the main hoisting shaft. It was the focus of all the mining operations because its position on the axis of the Tarkwa Syncline provided access to both limbs of the syncline. The Apinto and the Fanti South shafts are inclined, and are situated to the north of the AVS; 4 km and 4.8 km on its west and east limbs respectively. The AVS and Apinto shafts are connected along the 12 and 14 levels. The AVS is also connected to Fanti shaft along the 20 level.

GFGL operated the underground section up to 1999, when it was closed down to concentrate on its surface operations (Brewster, 2004). This abandoned underground mine began to flood in 2003. The projected surface area worked from the abandoned Tarkwa underground mine is estimated to 7.04 km^2 to a maximum depth of about 970 m. It is estimated from various sources that the Tarkwaian from the Tarkwa area has produced over 9.5 million ounces of gold from 1902 to 1998, or about 100 000 ounces per year (Karpeta, 2000). GFGL is currently incurring a substantial cost for pumping out water from the underground mine, after the rising water reached a decant point in 2002, approximately three years after cessation of pumping and mine abandonment. This valuable underground water resource is pumped out and discharged into a dam, from where it flows into the Bediabewu stream, and finally into the Bonsa River; the main source of water supply for the Tarkwa Nsuaem Municipality (TNM).

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The relatively high gold price in recent years has led to the development of large and small-scale gold projects in the Tarkwa gold district, with consequent increase in population in the TNM over the past decade. Illegal small-scale mining activities have also increased in the Tarkwa area and washing of the ore in and along the banks of the Bonsa River has resulted in its siltation and contamination. This has resulted in high treatment cost of the Bonsa River by the Ghana Water Company Limited (GWCL) and supply difficulties, leading to inadequate water supply to the municipality. GWCL water supply capacity to the TNM currently stands at 1 million gallons/day even though approximately 3 million gallons/day is required for normal supply to the municipality (Oteng Mensah, Pers. Comm., 2014). It has also been established that annual ratio of water produced by GWCL in Tarkwa to population growth from 1987 to 2008 has decreased from 76 litres/person/day to 40 litres/person/day (Kuma and Ewusi, 2009). GWCL attempted mitigating the problem by drilling some mechanised boreholes within the municipality to augment the existing water supply capacity, but the project was unsuccessful due to lack of funding and supply challenges (Oteng Mensah, Pers. Comm., 2014). As an interim measure GWCL is considering impounding the Bonsa River channel, to increase the discharge capacity, as well as increase the capacity of the treatment plant so that it can meet its current consumer's demand. However, the increasing level of contamination by human activities along the river with its resultant high treatment cost has proved a major challenge to increasing water supply. There is therefore the need to look for alternative sources of potable water supply which are sustainable for the municipality. This paper aims at estimating the volume of underground mine water in the AVS at GFGL, and if found suitable, recommend its use as an alternative water source to meet the rising demand, or to augment the supply from GWCL to the TNM area.

Mine Water: Banks *et al.* (1997) have exhaustively discussed mine water quality and their use. Use of mine water depends on its chemical and physical quality. If the quality criteria meet drinking water standards, mine water can be used as drinking water and several hundred small and large communities depend on such water supplies (Burbey et al. 2000, Teaf et al. 2006). Mine water is used as a primary or secondary source of drinking water at many locations around the world. In the U.S., 70 communities in the state of West Virginia use mine water and in most cases without any treatment other than chlorination (Hobba, 1987; Pack, 1992).

According Wolkersdorfer (2008), Freiberg and Breisgau in Germany are cities that supplement their drinking water reservoirs with mine water when necessary. Wolkersdorfer (2008) also lists at least 49 abandoned mines in the Rhenish Schiefergebirge, with discharges between 1 and more than 80 L s^{-1}, that are used for drinking water purposes. In the German Harz Mountains, the Teichtalstollen adit near Konigshutte is used as a secondary drinking water supply. Mine water is also used to drive turbines, for power plant cooling and process water (Wolkersdorfer, 2008). However, long term monitoring strategies are necessary to provide early warning for unforeseen events from mine water use (Annandale *et al.*, 2009). Underground mine waters have also commonly been used in spas, especially for people with diseases of the respiratory tract. One of the most prominent European spas associated with underground mining is Bad Gastein in Austria.

2 Resources and Methods Used

2.1 Resources

2.1.1 The Study Area

Tarkwa mine falls within the Southwestern equatorial climate zone of Ghana. The climate is primarily influenced by moist South-West monsoon winds from the South Atlantic Ocean, and dry dust-laden North-East trade winds known as the harmattan which blows over the Sahara desert from the northern sub-tropical high pressure zone. There are two rainy seasons, from March to July and from September to October, separated by a short cool dry season in August and a relatively long dry season in the south from November to March. The annual mean temperature is between 22°C and 35°C, with the highest temperatures recorded during February and March. The historical (1939-2014) average annual total rainfall is 1914 mm, a minimum of 1136 mm, and a maximum annual of 2986 mm. Fig.1 shows historical rainfall trends in the Tarkwa area. Relative humidity varies from 80 % to 95 %. During the harmattan season however, humidity drops to as low as 25 %.

2.1.2 Geology

The Tarkwa Basin is filled with a fining upward sequence of clastic sedimentary rocks known as the Tarkwaian Group which are of Proterozoic Age (2 132 to 2 095 Ma) and, comprise the Kawere Group, Banket Series, Tarkwa Phyllite and Huni Sandstone in order decreasing age. The Tarkwaian Group rests unconformably on the Birimian Super Group (Leube *et al.* 1990).

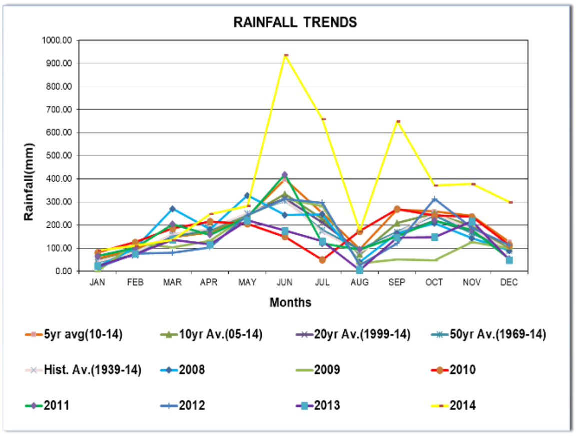

Fig. 1. Historical Rainfall Trends from 1939 to 2014

The sediments have been metamorphosed to low grade greenschist facies and are commensurate with a braided stream environment (Kesse, 1985). The Tarkwa mine site comprises gold bearing Banket conglomerate rocks with the country rock made up of sericitic quartzite resting on the metavolcanic Birimian units. The formation of the Banket conglomerate is exhibited in a series of synclines and anticlines extending over a distance of 16 km to the northeast. A feature of the area which has a considerable impact on mining operations is the incidence of reverse faults sub-parallel to the strike which cause repetitions or overlaps of the reefs of up to 250 meters on dip (Hirdes and Nunoo, 1994). These faults have the most effect on the AVS operations. Fig. 2 is simplified Geological Map of the Tarkwa Area.

The topography of the study area is dominated by pronounced ridges and valleys. The ridges are composed of the Banket Series and Tarkwa Phyllites with the low lying areas dominated by sandstones/quartzites. The ridges and valleys are parallel to one another and to the general NE-SW strike of the underlying geology, a feature which lends itself to the pitching fold structures and dip and scarp slopes in the Banket Series and Tarkwa Phyllites (Whitelaw, 1929). Transverse to the ridges and valleys are smaller valleys and gaps determined by faulting and jointing (Whitelaw, 1929). The central areas of the GFGL lease is low lying however, the lowest point of the catchment area lies to the northwest of Tarkwa.

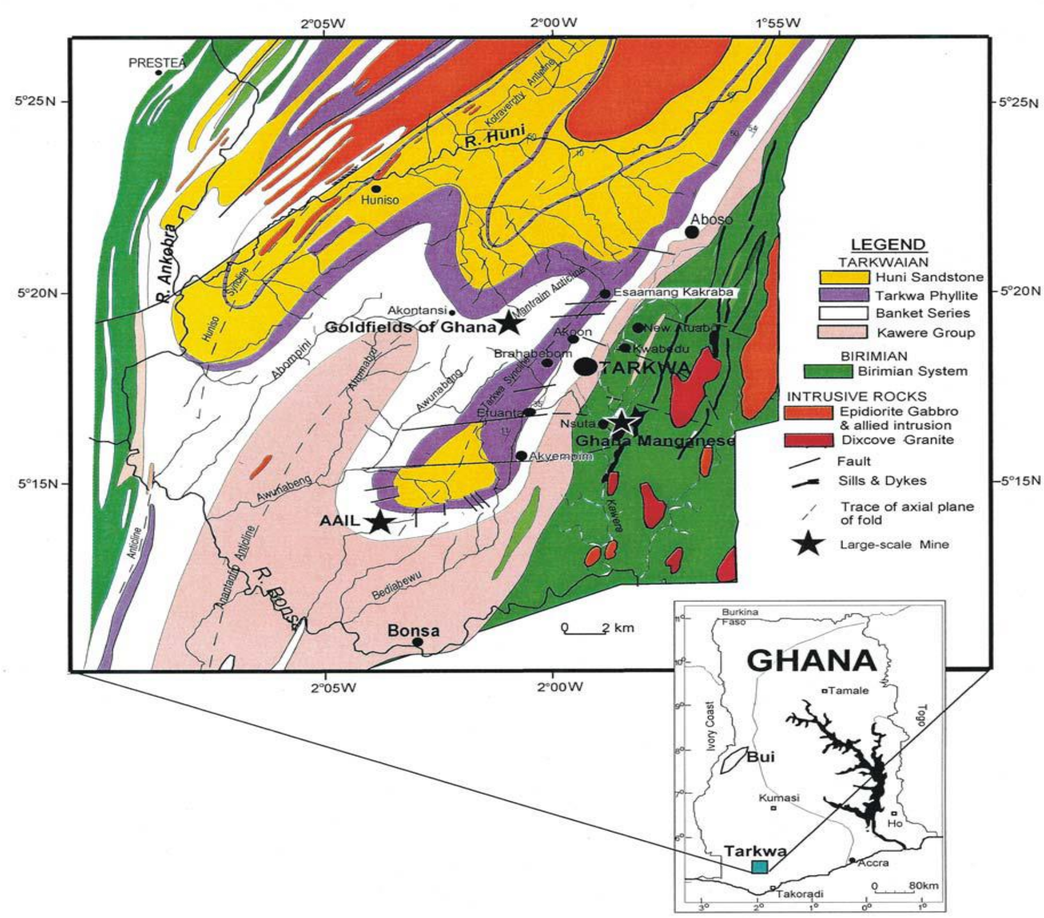

Fig.2 Simplified Geological Map of the Tarkwa Area (Modified from Junner *et al*, 1942)

2.1.3 Hydrogeology

Tarkwa falls within the Ankobra River Basin, which is an extensive drainage basin. The drainage pattern is mainly dendritic, reflecting horizontal and granular strata with signatures of rectangular and trellis patterns, which are respectively attributed to jointed and folded strata (Stone, 1999). The area is drained by a large number of streams and rivers. The most important of these are the Huni, Summang, Aberewanko, Abonko, Pepe, Ahomabrew, Awunaben, Kawere and the Bediabewu Rivers. The two most important are the Bonsa and the Summang Rivers as sources of water for the Tarkwa-Nsuaem Municipality. Apart from providing an opportunity for fishing for local inhabitants, the rivers serve as a source of drinking water and for irrigation. Several of the streams and rivers dry up or experience reduced flow during the dry seasons of the year, while flooding during the rainy seasons is common.

Groundwater occurrence in the Tarkwa area is associated with the development of secondary porosity through fissuring and weathering. In the Tarkwaian Group and especially in the Banket Series and Tarkwa Phyllites, the weathering depths rarely exceed 20 m. Clay, silts, sandy clays and clayey sands are mostly the result of the weathering. Recharge of groundwater in the Tarkwa area occurs mainly by direct seepage or infiltration through permeable surface strata which results in a generally shallow groundwater table. In this area, two types of aquifers occur. The weathered aquifer occurs mainly above the transition zone between fresh and weathered rocks. Due to the presence of clay and silt, these aquifers have high porosity and storage but low permeability. The fractured/fissured zone aquifer occurs below the transitions zone. They have relatively high transmissivity but low storativity (Kortatsi, 2007). Low conductivity values of the groundwater in the area indicate that the water is unable to react with the rock matrix to equilibrium which indicates short resident times (Kortatsi, 2007).

Large volumes of surface runoff are retained in natural swamps as well as in man-made lakes in close proximity to the mining areas. In some places groundwater is in hydraulic contact with rivers, and recharge from them can also take place (Kortatsi, 2007). Due to the depositional environment and structural development of the area, considerable variation in the thickness of the individual beds is expected. Therefore, aquifers with dual and variable porosity, limited area extent and storage properties should be the norm of the Tarkwaian. Even within an aquifer, folding of the whole area with the widespread presence of joints, faults, fissures and dykes further enhances this variability (Kuma and Younger, 2000). Based on the grouping of groundwater flow systems made by Toth (1963), local groundwater flow systems should be prevalent in the terrain (Kuma, 2004). Conceptual groundwater flow directions show that the two ridges of Banket Series and Tarkwa Phyllites form a water divide and partition the area into two i.e. the northern and southern sectors. On the assumption that both surface and groundwater are hydraulically connected, groundwater flow in the southern sector divide is due S and S-SW. In the northern sector, ground water flow directions are generally to the NW, but inferred to be SW near the nose of the Huniso Syncline (Kuma and Younger, 2000).

2.1.4 Description of the Underground Workings

The Abontiakoon Vertical Shaft (AVS) is a five-compartment shaft from surface to 28 level, which was sunk in 1935 to exploit deeper ore on the Abontiakoon underground mine. Mining method was by room-and-pillar, with long rib pillars of 3 m left between adjacent twin pillars. In the room-and-pillar development, 3.66 m rooms were separated by 2.44 m pillars. Stoping method used was largely underhand stoping, with ‘gutter’ stopes having an average inclination of 70^{o}, and average stope width of 1.52 m. The levels were horizontal and at average vertical interval of 30.48 m.

The lowest mine floor is at 850 m below sea-level, and the shaft collar is at 112.54 m above sea-level. Thus, calculated distance from collar to the lowest mine floor is 962.39 m. The shaft has a rectangular cross section with dimensions 9.45 m x 2.54 m, and an estimated vertical height of 624.09 m. The projected surface area worked from the AVS underground is about 3.7 km^2. The mine drives dimensions were 3 m x 2.44 m. Main raises were developed at every 60.96 m with dimensions of 1.83 m x 1.22 m. Rooms were advanced 7.62 m to 9.14 m to pass the last holing before a new room was created on strike. The standard layout for pillars in the AVS is as shown in Fig 3, and Fig. 4 is a longitudinal vertical projection of stoped-out areas in the West Limb-West Reef (WL-WR) section, a compartment of the AVS. About 16 percent rock material was left as pillars in the AVS (Acquah, 1997).

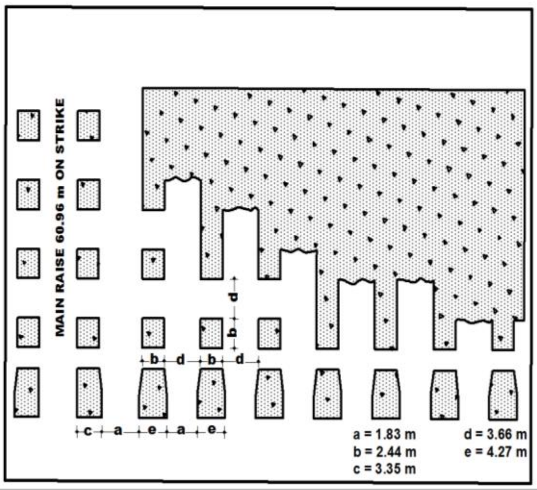

Fig. 3 Standard Layout for Pillars at GGL (modified from Acquah, 1997).

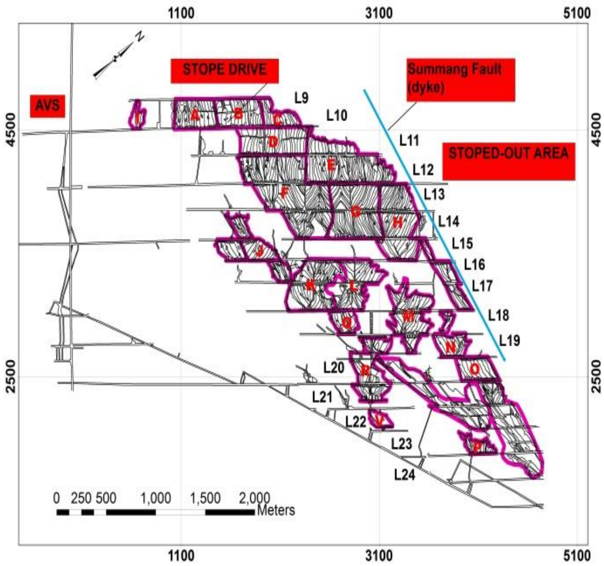

Fig. 4 Longitudinal Vertical Projection of Stoped-out Areas in the WL-WR Compartment of the AVS.

2.2 Methods Used

2.2.1 Void Volume Estimation

Void Volume Estimation in WL-WR

The mined-out sections for the WL-WR compartment of the AVS were available and this data was employed to estimate its total void volume. The estimate involved calculation of the areas of open voids from vertical sections as well as manual calculations for the shaft and conveyor routes. The respective areas of voids (stopes and conveyor routes) were then multiplied by their respective average width to estimate void volume.

The total void volume consists of void volumes in both underground developments and stoping as in Equation 1.

$$V_T = \text{A x W} \qquad (1)$$

Where, V_T is the total volume of voids (m^3), A is the total vertical Area of void (m^2) and W is the width of void (m).

The volumetric porosity of the rocks in the flooded underground workings was assumed to be negligible and adjustments for subsidence were not considered in this volume estimation.

Areas of mined out voids were determined by two approaches, The first approach involved digitising the vertical section of the open stopes using ArcGIS software, which automatically calculates each stoped-out area digitised, and then summed-up to obtain total area. The second method employed the use of a Sokkia PLACOM KP-90N digital planimeter to determine area. The accuracy of the planimeter is ± 0.2. The drawn sections were divided into blocks of voids labelled A to V, as shown in Fig. 4, and their respective areas determined for both approaches (Table 1).

The respective stope areas calculated were each multiplied by the average stope width of 1.52 m. Total estimated volumes for the stopes were 291 300 m^3 and 308 540 m^3 for planimeter and ArcGIS respectively, which averages to 299 920 m^3. The AVS underground mine stopes are inclined, with two sides (hanging wall and footwall) almost parallel. Thus, volumes calculated were independent of the slope angle (i.e. measurements were considered inside the inclined box dimensions and not the outside).

Volume of conveyor routes = Cross-sectional area x vertical height (2)

The standard dimensions of the drives are 3 m x 2.44 m. However, the areas of the ore-passes were estimated to be about a third of area of drives or 2.44 m^2 (Abban, Pers. Comm., 2011). Table 2 represents estimated volumes of the conveyor routes. Table 3 is a summary of the various components of the void volume, and total void volume in the mined-out WL-WR section.

Volume of the vertical shaft = Vertical Area x Vertical Height (3)

= (9.45 m x 2.54 m) x 624.09 m

= 14 980 m^3

Table 1 Areas and Volumes of Stopes Calculated by Planimeter and ArcGIS

PLANIMETER			ArcGIS		
BLOCK	Area (m^2)	Volume (m^3)	BLOCK	AREA (m^2)	VOLUME(m^3)
A	6 027.3	9 185.5	**A**	7 176.95	10 937.56
B	7 947.0	12 111.3	**B**	7 273.16	11 084.19
C	1 861.6	2 837.2	**C**	3 436.44	52 37.07
D	19 021.8	28 989.0	**D**	10 505.38	16 010.1
E	15 667.2	23 876.6	**E**	17 407.41	26 528.64
F	14 358.5	21 882.2	**F**	27 589.12	42 045.42
G	14 100.5	21 489.0	**G**	15 625.44	23 812.94
H	14 699.5	22 401.9	**H**	14 614.05	22 271.59
I	5 262.3	8 019.8	**I**	5 812.82	8 858.66
J	10 008.6	15 253.0	**J**	9 720.63	14 814.11
K	12 856.3	19 592.9	**K**	12 620.24	19 233.1
L	10 736.6	16 362.5	**L**	10 283.17	15 671.41
M	9 262.1	14 115.3	**M**	10 294.73	15 689.02
N	4 902.9	7 472.0	**N**	5 285.06	8 054.35
O	7 170.0	10 927.1	**O**	4 741.25	7225.6
P	2 469.9	3 764.2	**P**	1 535.72	2 340.42
Q	2 156.5	3 286.6	**Q**	2 881.80	4 391.84
R	8 626.2	13 146.2	**R**	10 848.20	16 532.49
S	10 911.7	16 629.4	**S**	7 716.77	11 760.24
T	10 119.2	15 421.5	**T**	14 032.65	21 385.55
U	1 373.2	2 092.8	**U**	1 405.09	2 141.35
V	1 603.6	2 443.9	**V**	1 647.33	2 510.51
TOTAL	**191 142.4**	**291 299.90**	**TOTAL**	**202 453.41**	**308 536.2**

The total volume calculated from void sections of the WL-WR does not include:

i) Mined-out void sections from the start for production in the AVS in 1935 to 1960 (due to Second World War disruption).
ii) Void sections from deeper levels: 25 to 28 (data unavailable).

Considering the above limitations, as well as available data and information on mine history which suggests effective production in the AVS was started around 1960 coupled with improved production levels in the later part of the mine production period, a more conservative actual estimate for void volume in the WL-WR is expected to be +20 % more than the 411 268 m^3 estimated or 493 522 m^3.

Void Volume Estimation in AVS

Two methods were used in estimating the total void volume in the mined out section of the AVS. The first method involved the use of a 30-year average monthly tonnage mined from survey production figures in the AVS, and total tonnage converted to total volume, to estimate total material mined-out.

Table 2 Estimated Volumes of Conveyor Routes

Level	Height (m)	Avg. Area(m^2)	Volume (m^3)
9	437.7	7.3	3 195.21
10	754.7	7.3	5 509.31
11	581.6	7.3	4 245.68
12	1 136.9	7.3	8 299.37
13	759.6	7.3	5 545.08
14	1 054.6	7.3	7 698.58
15	690.7	7.3	5 042.11
16	624.2	7.3	4 556.66
17	910.1	7.3	6 643.73
18	544.4	7.3	3 974.12
19	519.4	7.3	3 791.62
20	1 327.7	7.3	9 692.21
21	541.3	7.3	3 951.49
22	334.1	7.3	2 438.93
23	395.0	7.3	2 883.50
24	278.0	7.3	2 029.40
25	170.7	7.3	1 246.11
26	182.9	7.3	1 335.17
27	182.9	7.3	1 335.17
28	182.9	7.3	1 335.17
conveyor	1 346.6	7.3	9 830.18
ore pass	746.2	2.4	1 790.88
Total			**96 369.68**

Table 3 Calculated Volumes and Expected Total Volume in the WL-WR

Vol. of Shaft	Vol. of Open Stopes	Vol. of Drives and Conveyors	Total void Vol. in WL-WR	Expected Total void in WL-WR (+20% of calculated)
14 980 m^3	29 9918 m^3	96 370 m^3	**411 268 m^3**	**493 522 m^3**

(a) Estimating Mined-Out Volume Based on Survey Production Figures from AVS

The calculated weighted monthly average tonnage from 30 years (1970-1999) survey production figures in the AVS was used to estimate actual volume of material mined-out from the AVS to be 16 193 tonnes/mth (Table 4). From mine history, effective production years of operations in the AVS started from 1960-1999 (40 years). Therefore, the estimated tonnes mined from all five-compartments of the AVS underground over its operation period is calculated as in Equation 4.

$$\frac{16\,193\ tonnes}{month} \times \frac{12\ months}{year} \times 40\ years = 7\,772\,640\ tonnes \quad (4)$$

Thus, using a Specific Gravity (S.G.) of 2.8, the estimated volume of material moved from AVS void is 2 775 943 m^3.

(b) Estimating AVS Mined-out Volume from Post Closure Void Filling Parameters

Final dewatering rates in the AVS mine together with duration for mine inundation was also used to arrive at an estimate for the AVS mined-out void volume. Records of dewatering rates of the AVS underground just before mine closure were not found, but it is known that pumping in AVS started from the 14 level, with average pumping rate just before final mine closure in December 1999 of about 400 gals/min (955 570 m^3/year or 2 618 m^3/day) (Buckle and Kulaare, Pers. Comm., 2011).

According to Asmah (Pers. Com., 2011), if the AVS water is lowered below a depth of about 42 m (70.54 mRL) from surface, discharge water from pumping in the inclined Fanti shaft located 4.8 km north of AVS, and on the east limb of the Tarkwa syncline would cease.

The duration for the GFGL underground mine water inundation after pumping ceased was about 3 years. Thus, the total volume of water expected to completely fill the AVS void is calculated from Equation 5.

$$\frac{955\,570\ m^3}{year} \times 3\ years = 2\,866\,710\ m^3 \quad (5)$$

The estimated volume of water in the AVS void filled completely with water is therefore 2 866 710 m^3.

Table 4 AVS production figures from 1970 to 1999

Year	Tonnes Mined		Ounces of Gold	
	Monthly	Yearly	Monthly	Yearly
1970	26 608	319 301	3 796	45 551
1971	21 852	262 221	3 656	43 871
1972	20 931	251 168	4 405	52 861
1973	22 461	269 532	4 653	55 832
1974	22 944	275 324	4 531	54 370
1975	24 580	294 956	4 789	57 466
1976	24 508	294 096	4 860	58 319
1977	25 285	303 416	4 689	56 271
1978	24 833	298 000	4 411	52 931
1979	20 288	243 452	3 268	39 217
1980	19 624	235 490	3 241	38 897
1981	16 033	192 390	2 711	32 529
1982	13 870	166 440	2 599	31 186
1983	8 026	96 310	1 346	16 156
1984	8 579	102 950	1 203	14 435
1985	8 220	98 640	1 118	13 416
1986	6 763	81 160	1 291	15 493
1987	9 997	119 960	1 522	18 260
1988	11 763	141 150	1 671	20 053
1989	10 933	131 200	1 711	20 528
1990	13 208	158 500	2 047	24 568
1991	12 262	147 140	2 300	27 594
1992	12 168	146 020	2 213	26 551
1993	8 146	97 751	1 407	16 889
1994	16 732	200 785	2 891	34 691
1995	18 725	224 697	3 235	38 822
1996	20 018	240 212	3 459	41 503
1997	19 843	238 118	3 429	41 141
1998	8 302	99 628	1 434	17 213
1999	8 292	99 500	1 433	17 191

(c) Estimating Mined-Out Volume Based on Survey Production Figures for the Entire Mine

According to Karpeta (2000), total underground gold produced from Abontiakoon, ABA and Tarkwa Gold Mine, was estimated to be just over 5 million ounces (5.0 Moz) from over 47.3 million tonnes (47.3 Mt) of ore. Additionally, it has been estimated from various sources that the Tarkwaian in the Tarkwa area has produced over 9.5 million ounces (9.5 Moz) in the period 1902 to 1998. From the above information, and with an average ratio of mined tonnes to milled tonnes of 1:0.9 (from mine records), and for Specific Gravity of 2.8, the estimated total void volume created in the Tarkwa underground operations from 1902 to 1998 is:

$$\frac{\left(47.3\ Mt \times \frac{9.5\ Moz}{5.0\ Moz}\right)}{2.8} = 32 \times 10^6\ m^3 \quad (6)$$

Thus, if all voids are filled with water, the amount of water in the Tarkwa underground reservoir is on the order of 3.2 x 10^7 m^3.

2.2.2 Analysis of AVS Underground Reservoir Characteristics Using Rainfall, Water Elevation and Pumped Volumes Inter-Relationships

(i) Meteorological data was collected from 2008 to 2014 (7-years) from point rainfall records. Six rain gauges installed around the study area were employed.

(ii) Pumping started just after the mine got flooded and water seepages into low-lying areas around the mine were observed. Pumping data was obtained from daily records from two Grundfos submersible pumps installed to a depth of about 60 m below the ground surface. Pumping was done continuously, 24 hours per day.

Daily pumping is still on-going and discharged into a near-by man-made dam, which finally discharges into the Bonsa River via the Bediabewu stream. The underground water is treated and used to augment domestic water supply to the mine's residence during dry periods when supply from boreholes become inadequate.

(iii) Daily depth-to water level measurements from an established datum was used during the 7-year period to determine the variability of water level fluctuations in the AVS in order to characterise the hydrologic behaviour of the underground water system. Plots of the 7-year average rainfall, pumped water volumes and water elevation records are as presented in Figs. 7 and 8. The water elevation records were averaged over a 12-month period to reduce seasonal fluctuations (See Table 5 and Fig. 9).

Table 5 Yearly Average Quantity of Water Pumped and Corresponding Water Level

Year	Yearly Pumping $(m^3)x10^3$	Yearly Average Water level(m)
2008	1 328	70.38
2009	940	72.30
2010	774	74.49
2011	573	76.48
2012	880	72.45
2013	728	73.45
2014	701	76.01

2.2.3 Water Sampling

Samples of pumped out mine water discharges from the AVS were analysed in order to have a fair knowledge of the mine water quality. Two samples were collected in November of 2011 and February of 2015 and analysed. Unavailability of a depth-sampling equipment did not permit depth sampling of the shaft water. Parameters such as water pH, temperature, conductivity and total dissolved solids, were evaluated on the spot during sample collection whiles other water quality parameters were analysed at the laboratory and summarised in Table 6.

2.2.4 Recharge Estimation

Estimating recharge in a complex reservoir system like an abandoned underground void is normally challenging, and where data gathering for this purpose is not deliberately undertaken; a *priori*, independent means is normally employed (Younger and Adams, 1999). The simple mathematical model of predicting rebound on a "*void filling*" basis was attempted. This model predicts rebound by determining the volume of ore extracted in a given mine pond or mining district, then compares this volume to the long-term average recharge rate. Also, where the water make of a particular mine system had few head-dependent components, the total dewatering rate during peak production provides a useful upper-bound estimate for the rate of recharge to the workings. Even where the head-dependent component of the water make was substantial, the total dewatering rate provides one of the two terms needed to calculate the long-term recharge rate (Younger and Adams, 1999).

Using the calculated estimate of volume (V) in m^3 of material extracted from the AVS void, and the approximate mine water rebound period (T) in years, the rate of rebound (Q) in m^3/year was estimated from the relation in Equation 7.

$$Q = \frac{V}{T} \quad (7)$$

3 Results and Discussion

3.1 Reservoir Analysis and Water Sampling

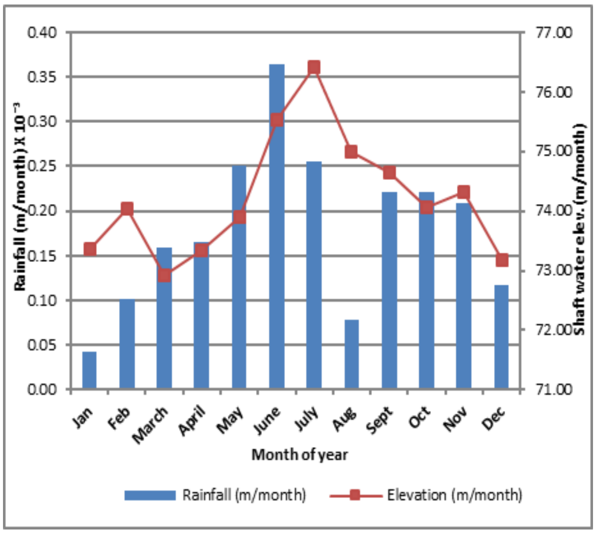

Fig.7 Seven (7)-year Average Rainfall vs. Water Elevation.

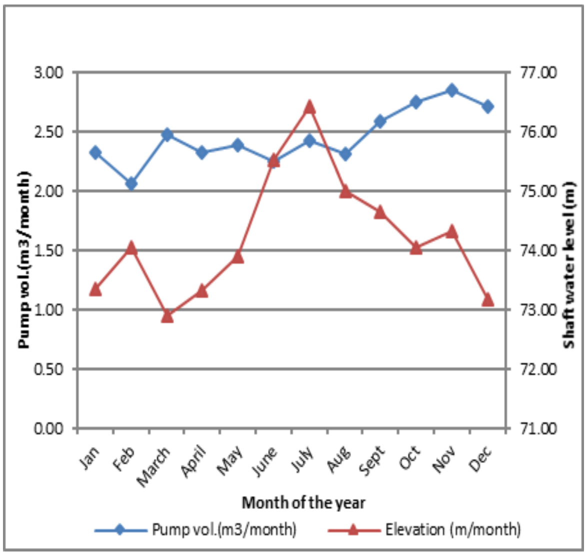

Fig.8 Seven (7) -year Average Water Elevation vs. Pumped Volumes.

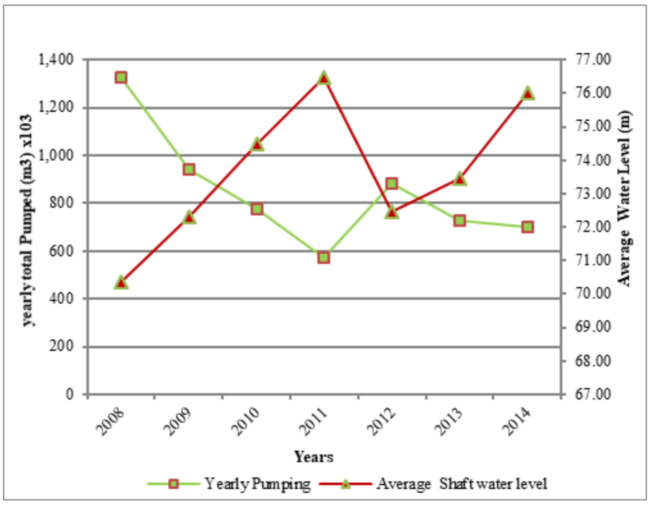

Fig.9 Average Groundwater Elevations vs. Yearly total Pumped (2008-2014).

The 7-year average daily pumping rate was 2 457 m^3/day (846 351 m^3/year), with corresponding shaft water elevation of 73.45 m and mean daily change in water level of +0.003 m. Maximum and minimum depth-to water measurements for the period were 79.34 m and 67.55 m respectively.

It is observed from Figs 7 and 8 that the AVS water elevation generally responds to both seasonal variations and pumping; lower elevations were recorded for low rainfall months (October-February) and high pumping rates. Conversely, high water elevations were measured for high rainfall months (March-July) and also for reduced pumping capacities. This suggests that the AVS underground water level does not only depend on the pumping rates, but also on rainfall. The wettest month was in June, with January being the driest.

With the estimated average volume of material extracted from the AVS being 2 775 943 m^3 and rebound took 3 years, the estimated recharge using the "void filling" method is 2 535 m^3/day.

The 7-year average daily post-closure (after flooding) pumping rate during the study period was determined to be 2 457 m^3/day. Also, the estimated daily average dewatering rate which may be used as a possible recharge rate during the period of active operations underground just before mine closure as 2 618 m^3/day. These three results are quite comparable and the actual recharge rate is likely to be within 2 457 m^3/day and 2 618 m^3/day.

A firm conclusion can be drawn for the long-term use of the water.

Generally, the water quality in the AVS was essentially analysed for domestic use, and in accordance with guidelines of World Health

Organisation (WHO) and Environmental Protection Agency Drinking Standards (EPADS).

Results from analysing the samples indicate neutral conditions for the shaft water, with average pH of about 7.24, which is within the WHO recommended pH range for drinking water.

Manganese concentration of 3.087 mg/L is far above the WHO guideline value for drinking water quality of 0.4 mg/L. The total hardness concentration of 234 mg/L makes the underground water reasonably hard. Regular depth sampling of the water for its chemical quality is required before a firm conclusion can be drawn for long term use of the water.

4 Conclusions and Recommendation

4.1 Conclusions

(i) Estimates for total mined-out void in the AVS underground calculated by two different methods for both surveyed production volumes and final mine dewatering rates were 2.8 x 10^6 m^3 and 2.9 x 10^6 m^3 respectively.

(ii) It was deduced that the Tarkwa underground mine has a potential water reservoir volume of approximately 3.2 x 10^7 m^3.

(iii) Recharge rates for AVS were predicted to range between 2 457 m^3/day and 2 618 m^3/day.

(iv) The estimated recharge rate of 6 x 10^5 gals /day for the AVS water reservoir can be used to off-set about 30 % of the current daily water supply deficit in the TNM, and at a relatively cheaper cost. However, large-scale pumping from the underground is possible, considering the potential volume of water in the Tarkwa underground void.

Table 6. Summary of Physico-Chemical Water Quality Parameters in the AVS

PARAMETER	EPA (GHANA)	PERMISSIBLE UPPER LIMIT (WHO STANDARD)	RESULTS OF ANALYSIS (NOV. 2011)	RESULTS OF ANALYSIS (FEB. 2015)
pH	6.5-9.0	6.5-8.5	7.4	7.08
TDS (mg/L)	1000	1000	421	440
ECond(µS/cm)	750	1500	693	656
DO(mg/L)		>5.0	4.1	8
Temp (°C)		<3°C aa	24.2	27
TSS (mg/L)		50	5.93	7.83
Colour (Apparent) PtCo		200	135	160
Colour (True)PtCo			2	28
CN^-(mg/L)		0.01	0.001	0.004
NO_3^-(mg/L)	10	50	2.6	0.2
SO_4^- (mg/L)	250	250	190	85
$C1^-$	250	250	4.2	6.7
Alkalinity (mg/L)	150	200	175	185.5
Cu(mg/L)	1	1	0.007	<0.01
Cd(mg/L)			-0.002	<0.002
Cd(mg/L)	0.05	0.4	3.087	2.73
Mn(mg/L)		30	6.344	34.95
K(mg/L)			3.304	2.81
Na(mg/L)	200	200	7.592	16.67
Ca(mg/L)		75	143.165	75.87
Fe(mg/L)	0.3	0.3	0.257	0.02
Zn(mg/L)	5	3	0.026	<0.01
T.COLI			261.3	
E. COLI		0	<1	<1
Total Hardness (mg/L)	1000	1000	1	234

(v) The water sampled from the AVS reservoir was from the surface and does not pose any quality problems or health threats.

(vi) Concentrations of the heavy metals are low and thereby have less impact on metal contamination in the underground water.

4.2 Recommendation

It is recommended from this study that with the net average daily rise of +0.003m in water level, and more over the estimated recharge rate being greater than the average daily pumping rate, pumping in the AVS underground reservoir will need to be increased to avoid surface discharges in the future.

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